Right-handed neutrinos and lljj searches in run 1

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Based on work in collaboration with Bogdan Dobrescu and Jacobo Lopez-Pavon,
arXiv: 1508.04129 (Phys.Rev. D92 (2015) no.11, 115023)

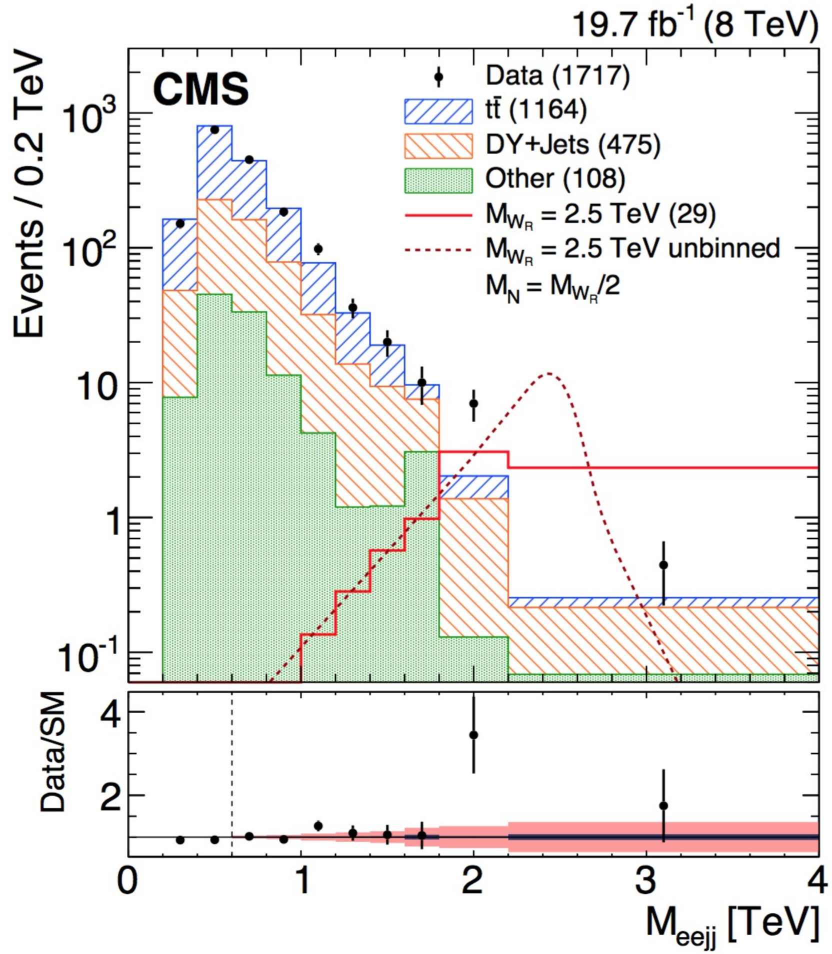
New physics Interpretations at the LHC
Argonne National Lab
May 2nd, 2016

Outline

- Motivation
- Our model
- High-energy phenomenology
- Low-energy phenomenology
- Conclusions

Motivation

- In 2014, CMS reported an excess in eejj events in a search for heavy neutrinos and W' bosons:



CMS collaboration
1407.3683

Motivation

- A few other excesses were also reported in run 1 searches:

    - W'$\to$ W Z $\to$ JJ (J is a merged jet)

      (3.4σ excess) ATLAS, 1506.00962

    - W'$\to$ W h^0 $\to$ lν $b\bar{b}$

      (2.2σ excess), CMS-PAS-EXO-14-010

    - W'$\to$ jj

      (2σ excess) CMS, 1501.04198

(More about this on Zhen Liu's talk)

Troubleshooting

- In principle, left-right models $SU(2)_L x SU(2)_R x U(1)_{B-L}$ contain all the ingredients needed: a W' and right-handed neutrinos

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  - No μμjj excess
  - Only opposite-sign events (13 out of 14 eejj events)

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- In principle, left-right models $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ contain all the ingredients needed: a W' and right-handed neutrinos
- Challenges to explain the eejj excess in the vanilla scenario:
  - No μμjj excess
  - Only opposite-sign events (13 out of 14 eejj events)
- Possible ways out:
  - The mass of the heavy muon right-handed neutrino is heavier than the W'
  - The heavy electron neutrino is mostly Dirac

Solutions

- Several ways to accomplish this. All of them need (pseudo-) Dirac N_R:
  - Add another particle as the Dirac partner
    e.g., Dobrescu, Liu, 1506.06736
  - Inverse Seesaw mechanism
    e.g., Dev and Mohapatra, 1508.02277
  - Linear Seesaw mechanism
    e.g., Deppisch et al, 1508.05940
  - Fine-tune the masses of the N_R
    e.g., Gluza and Jelinski, 1504.05568

Our model

Fields	Spin	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$
$(u_L,\ d_L)$	$1/2$	2	1	$+1/3$
$(u_R,\ d_R)$	$1/2$	1	2	$+1/3$
$(\nu_L,\ \ell_L)$	$1/2$	2	1	-1
$(N_R,\ \ell_R)$	$1/2$	1	2	-1
Σ	0	2	2	0
T	0	1	3	$+2$

(Minimal modification of the particle content in Dobrescu, Liu, 1506.06736 and 1507.01923)

Our model

- We impose a flavor symmetry to make the right-handed neutrinos Dirac particles:

$$L_R^e = (N_R^e, e_R)^\top$$ Charge +1

$$L_R^\mu = (N_R^\mu, \mu_R)^\top$$ Charge 0

$$L_R^\tau = (N_R^\tau, \tau_R)^\top$$ Charge -1

Triplet: neutral under flavor symmetry

$$-\frac{y_{\mu\mu}}{2}(\bar{L}_R^\mu)^c i\sigma_2 T L_R^\mu - y_{e\tau}(\bar{L}_R^e)^c i\sigma_2 T L_R^\tau + \text{H.c.}$$

Our model

- The triplet breaks the gauge group down to $SU(2)_L \times U(1)_Y$

$$\langle T \rangle = \begin{pmatrix} 0 & 0 \\ u_T & 0 \end{pmatrix}$$

- And it gives right-handed neutrinos a mass:

$$-u_T \left(\overline{N}_R^e, \overline{N}_R^\mu, \overline{N}_R^\tau \right)^c \begin{pmatrix} 0 & 0 & y_{e\tau} \\ 0 & y_{\mu\mu} & 0 \\ y_{e\tau} & 0 & 0 \end{pmatrix} \begin{pmatrix} N_R^e \\ N_R^\mu \\ N_R^\tau \end{pmatrix}$$

Our model

- After diagonalization, we end up with two heavy neutrino mass eigenstates:
  - A purely Majorana fermion, $N_{\mu,R}$
  - A purely Dirac fermion, $N_{1,R}$
- Interactions with the W' in the mass basis:

$$\frac{g_{\mathrm{R}}}{\sqrt{2}} W'_{\nu} \left(\overline{N}_{1_R} \gamma^{\nu} e_R + \overline{N}^{c}_{1_L} \gamma^{\nu} \tau_R + \overline{N}^{\mu}_{R} \gamma^{\nu} \mu_R \right) + \mathrm{H.c.}$$

Our model

- The flavor symmetry imposed gives rise to peculiar experimental signatures:

$$W'^+ \quad \to N_1 e^+$$

$$W'^+ \quad \to \overline{N}_1 \tau^+$$

$$W'^+ \quad \to N_R^\mu \mu^+$$

We forbid this kinematically

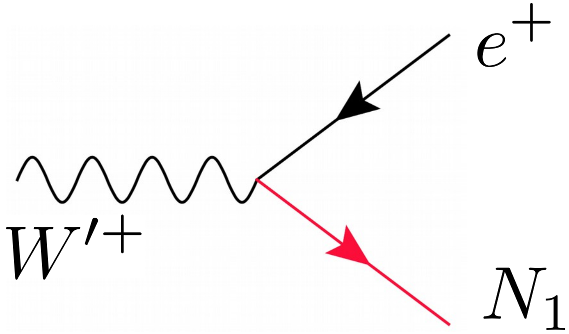
$$m_{N_R^\mu} > m_{W'}$$

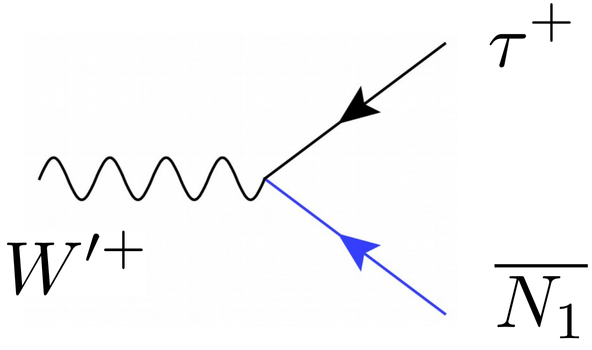
Our model

- The flavor symmetry imposed gives rise to peculiar experimental signatures:

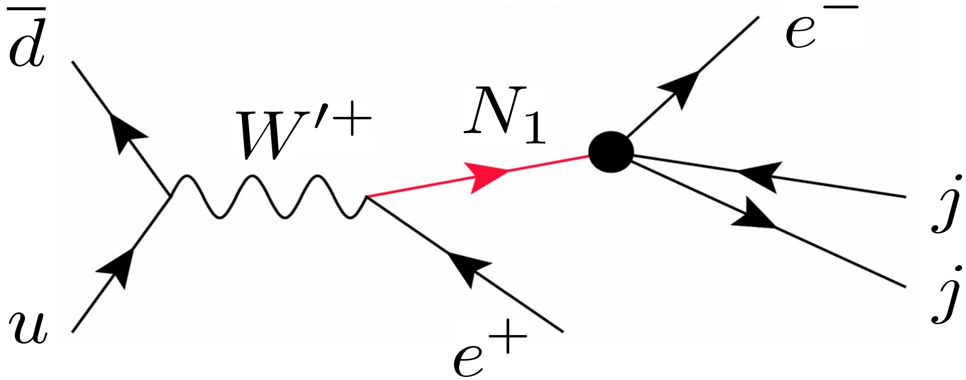
$$W'^{+} \quad \to N_1 e^{+}$$

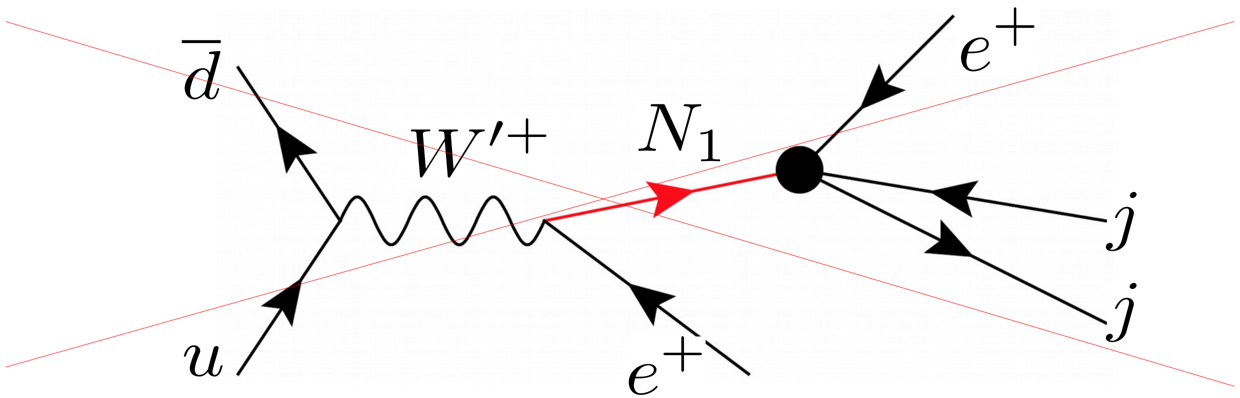
$$W'^{+} \quad \to \overline{N}_1 \tau^{+}$$





High-energy pheno: LHC





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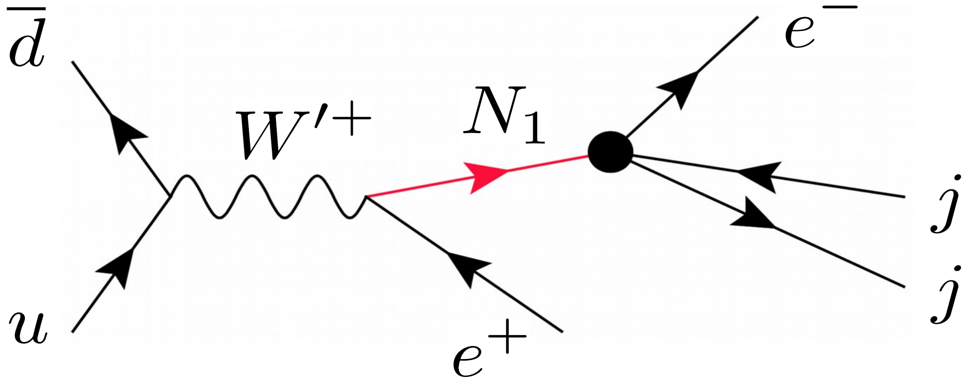
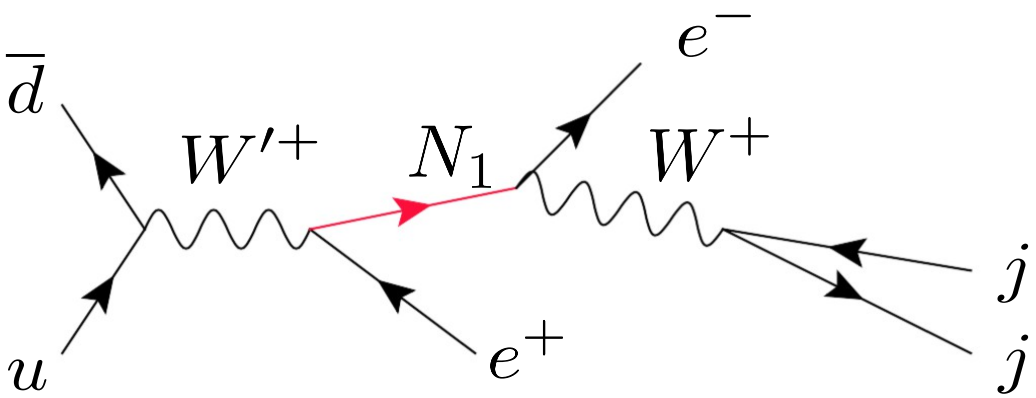


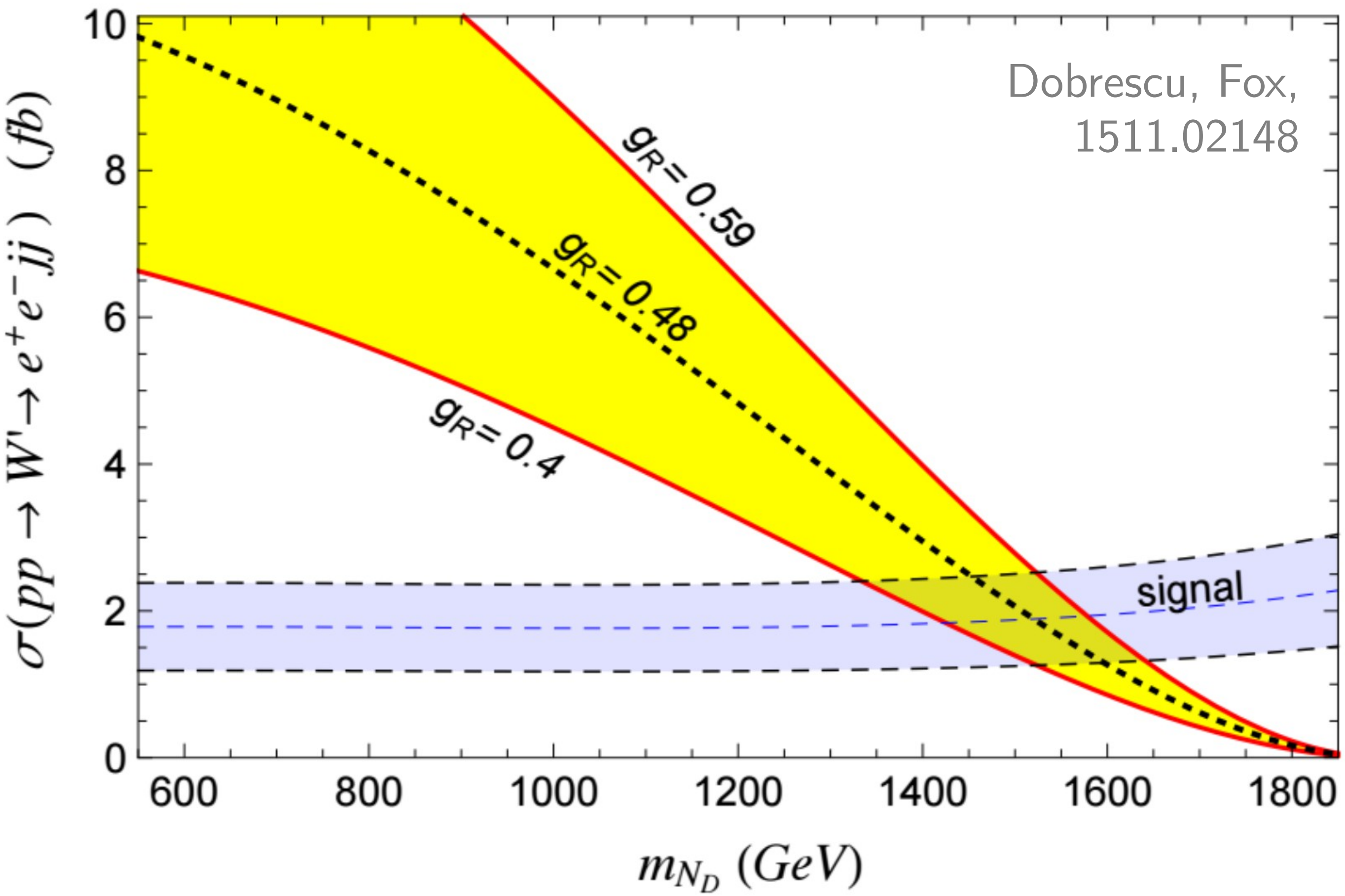
It is also possible to have a two-body decay via an on-shell SM W, but is suppressed due to the small mixing between W - W':



Dobrescu, Fox, 1511.02148

High-energy pheno: LHC

A comparison with the excess observed at run I allows to determine the allowed range for m_{N1}:



Low-energy pheno: neutrino masses

- Neutrino masses and mixing can be generated successfully with this model!!
- A singlet scalar, charged under the flavor symmetry, connects the light and heavy neutrino sectors:

$$\frac{C_{\alpha\beta}}{\Lambda^3}\phi\overline{L_L^\alpha}\tilde{\Sigma}T^\dagger T L_R^\beta \longrightarrow m_D = v_H \sin\beta \frac{\langle\phi\rangle u_T^2}{\Lambda^3} C$$

This generates Dirac mass couplings between light and heavy neutrinos

Low-energy pheno: neutrino masses

- After diagonalization, the light neutrino masses are suppressed via the See-Saw mechanism (type I):

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^t & M_R \end{pmatrix} \longrightarrow \quad m_\nu \sim m_D M_R^{-1} m_D^t$$

In order to get the right neutrino masses (eV),
m_D cannot be above MeV scale

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$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D^t & M_R \end{pmatrix} \longrightarrow \quad m_\nu \sim m_D M_R^{-1} m_D^t$$

- Minimal solution that reproduces right mixing parameters:

($N_{\mu,R}$ does not participate in the generation of neutrino masses)

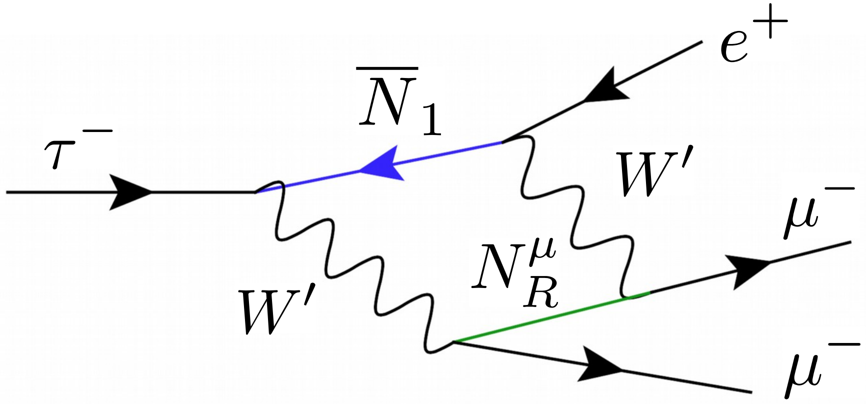
$$m_D = \begin{pmatrix} m_{11} & 0 & m_{13} \\ m_{21} & 0 & m_{23} \\ m_{31} & 0 & m_{33} \end{pmatrix}$$

(Lightest neutrino is massless)

Gavela, Hambye, Hernandez, Hernandez, 0906.1461

Low-energy pheno: LFV

$$B(\tau^- \to \mu^- \mu^- e^+) < 1.7 \times 10^{-8}$$



$$\propto g_R^8 \frac{M_W^4}{4\pi g M_{W'}^4} \sim 10^{-12}$$

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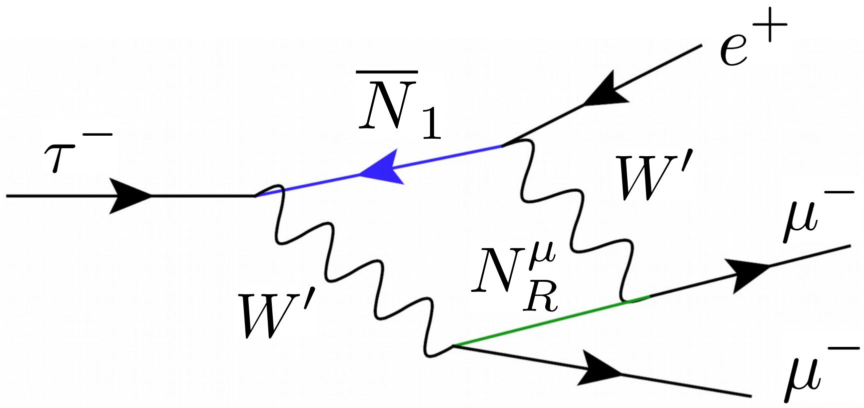
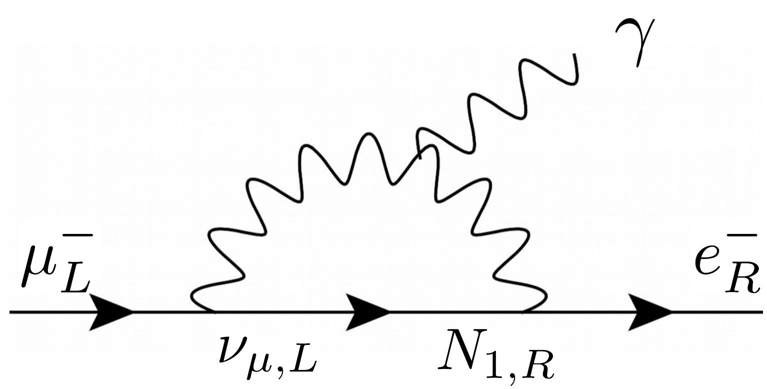


$$\propto g_R^8 \frac{M_W^4}{4\pi g M_{W'}^4} \sim 10^{-12}$$

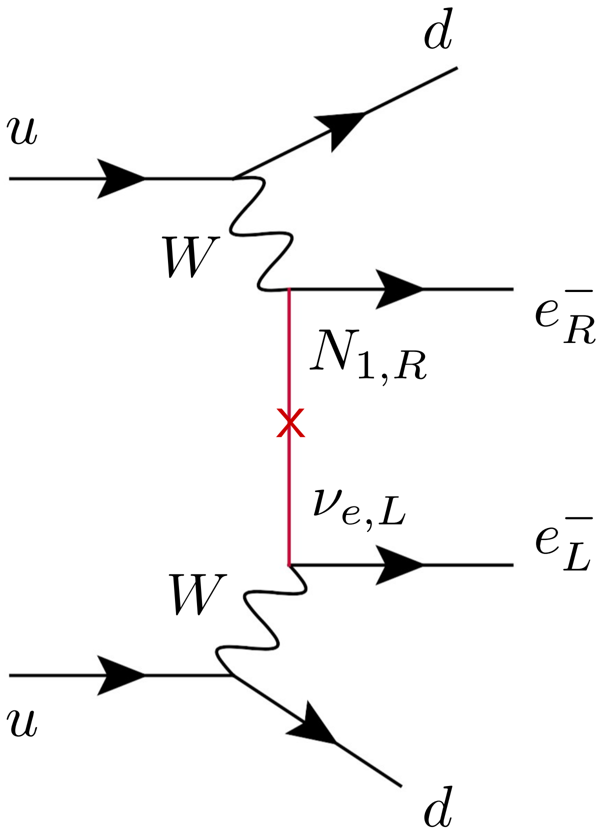
$$B(\mu^- \to e^- \gamma) < 5.7 \times 10^{-13}$$



$$\propto \left(\frac{\alpha}{\pi} \sin^2\theta_+\right) \left(\frac{m_{21}}{m_\mu}\right)^2 \sim 10^{-13}$$

Low-energy pheno: neutrinoless

The leading order contribution from the heavy neutrino sector is suppressed by $W_L - W_R$ mixing and heavy-light neutrino mixing:



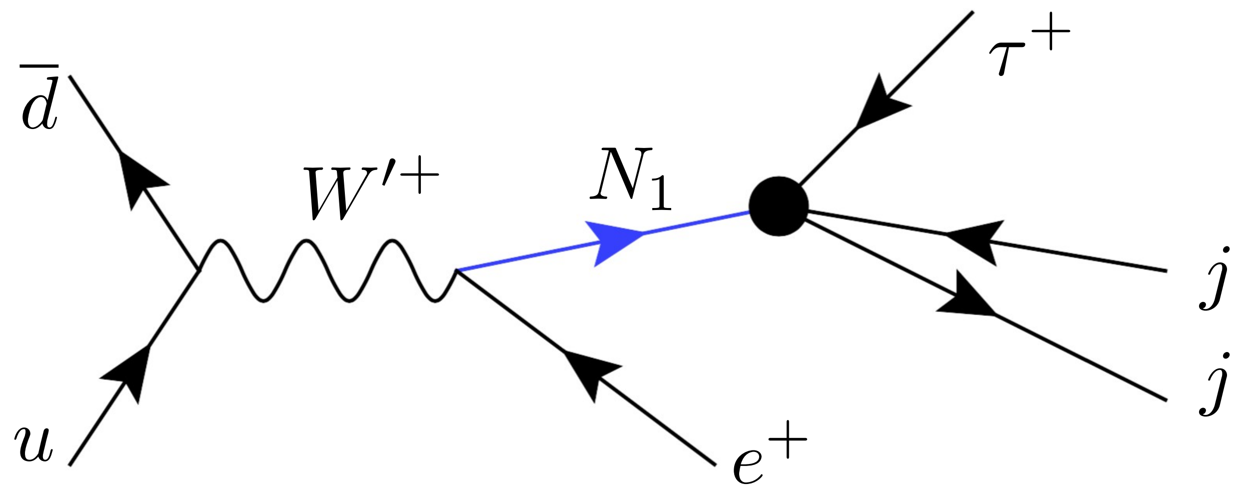
$$m_{0\nu\beta\beta} \sim \frac{g_R}{g} \sin\theta_+ \frac{m_{13}}{m_{N_1}} \langle p \rangle$$

Within reach of future experiments:

$$\left. \begin{array}{l} m_{13} \sim 0.3\,\mathrm{MeV} \\ m_{N_1} \sim 1.5\,\mathrm{TeV} \end{array} \right\} \Longrightarrow m_{0\nu\beta\beta} \sim 10\,\mathrm{meV}$$

Outlook

- There is a direct link between lepton number and lepton flavor violation in this model



$$
\begin{aligned}
B(W'^+ \to e^+ N_1 \to e^+ e^- jj) &= B(W'^+ \to \tau^+ \overline{N}_1 \to \tau^+ \tau^- jj) \\
&= B(W'^+ \to e^+ N_1 \to e^+ \tau^+ jj) \\
&= B(W'^+ \to \tau^+ \overline{N}_1 \to \tau^+ e^+ jj)
\end{aligned}
$$

Outlook

- Similar relations hold for processes in which the W‘ decays into lepton and tb, or WZ, e.g.:

$$\sigma(pp \to e^+\tau^+ b) + \sigma(pp \to e^-\tau^- \bar{t}b) = 2\sigma(pp \to e^+ e^- \bar{t}b)$$

- These predictions also affect the branching ratios of the Z’:

$$\begin{aligned} B(Z' \to \overline{N}_1 N_1 \to e^+ e^- + 4j) &= B(Z' \to \overline{N}_1 N_1 \to \tau^+\tau^- + 4j) \\ &= B(Z' \to \overline{N}_1 N_1 \to \tau^+ e^+ + 4j) \\ &= B(Z' \to \overline{N}_1 N_1 \to \tau^- e^- + 4j) \end{aligned}$$

Conclusions

- CMS observed an excess in eejj events in run 1
  - No lepton number violation observed $\rightarrow$ Dirac
- Due to our flavor symmetry, the electron and tau right-handed neutrinos combine as a Dirac particle
- The muon heavy neutrino should be heavier than the W'
- Our model can explain the smallness of neutrino masses and reproduce the flavor mixing pattern at low energies
- The flavor structure of the model protects it from lepton flavor violation bounds, and neutrinoless double beta decay
- The model can be tested at the LHC by looking for signatures involving tau leptons

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Thank you!!!

Backup slides

Low energy pheno: neutrino masses

- Neutrino and charged lepton Dirac masses can be generated by a d=4 operator. However, then they should be of the same order, or fine-tuning is required:

$$-\overline{L}_L^{\alpha}\left(y_{\alpha\beta}\Sigma+\tilde{y}_{\alpha\beta}\tilde{\Sigma}\right)L_R^{\beta}$$

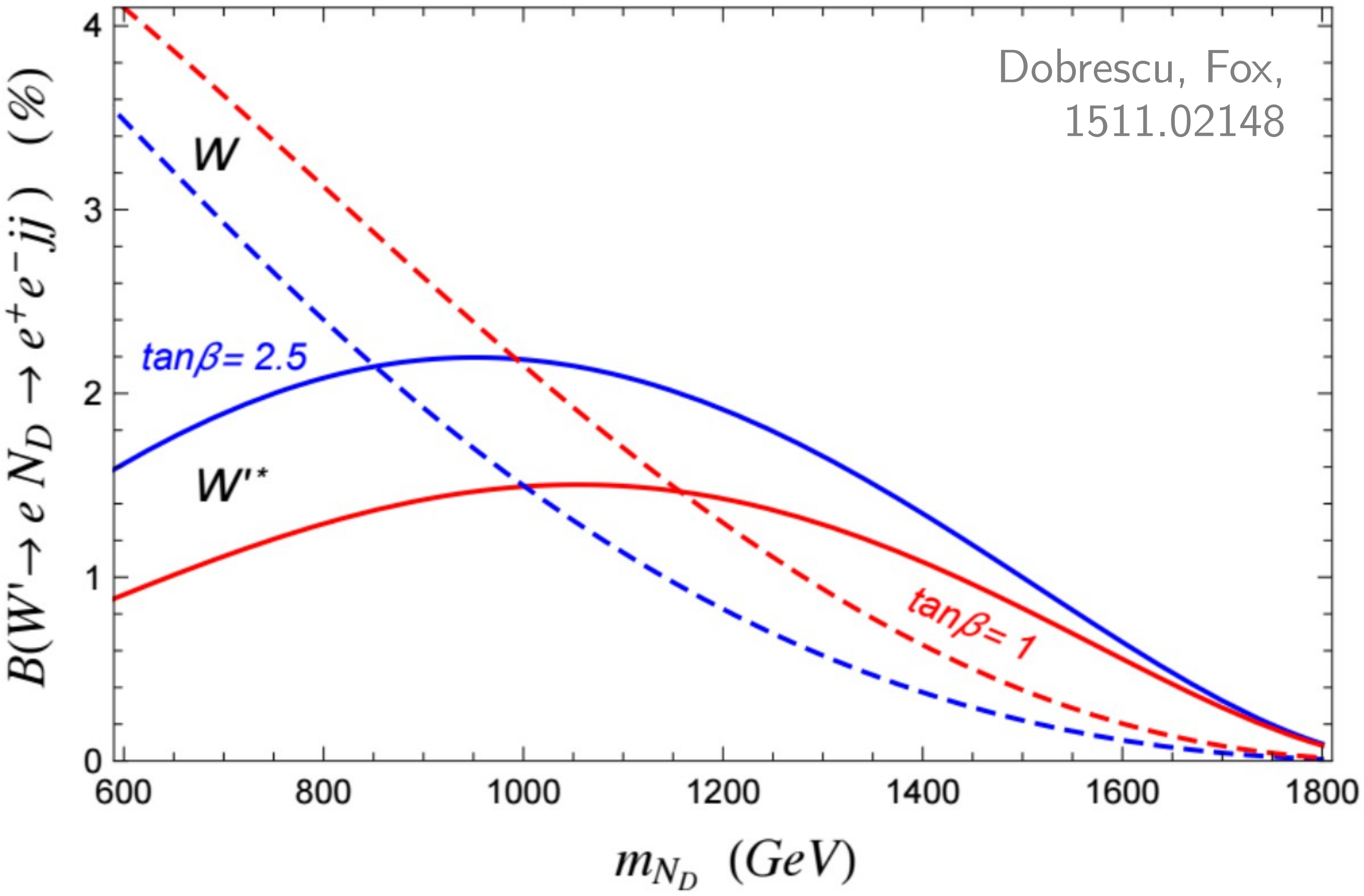
- Neutirno Majorana masses can also be generated through a d=6 operator. We assume these are negligible (although this does not change the general discussion):

$$\frac{\eta_{\alpha\beta}}{M^2}(L_L^{\alpha})^c\Sigma T\Sigma^{\dagger}L_L^{\beta}$$

PC, Dobrescu, Lopez-Pavon, 1508.04129

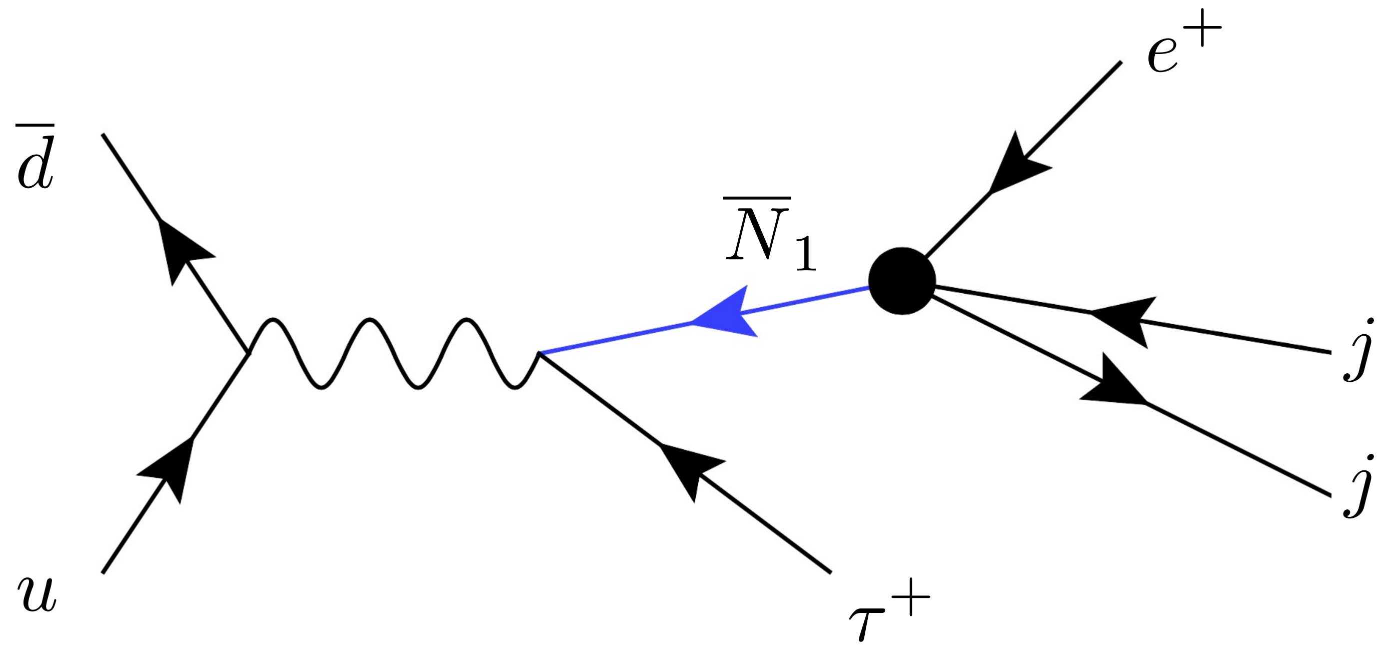
Branching ratios for the N_1

The heavy neutrino can decay via two- and three-body decays:

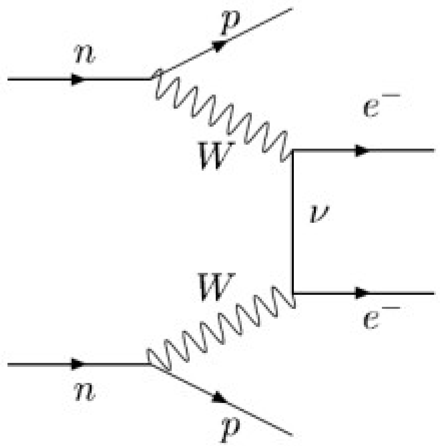


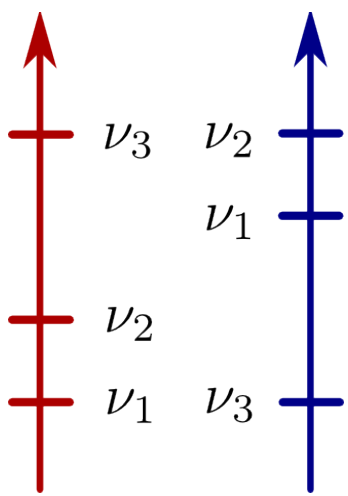
Outlook

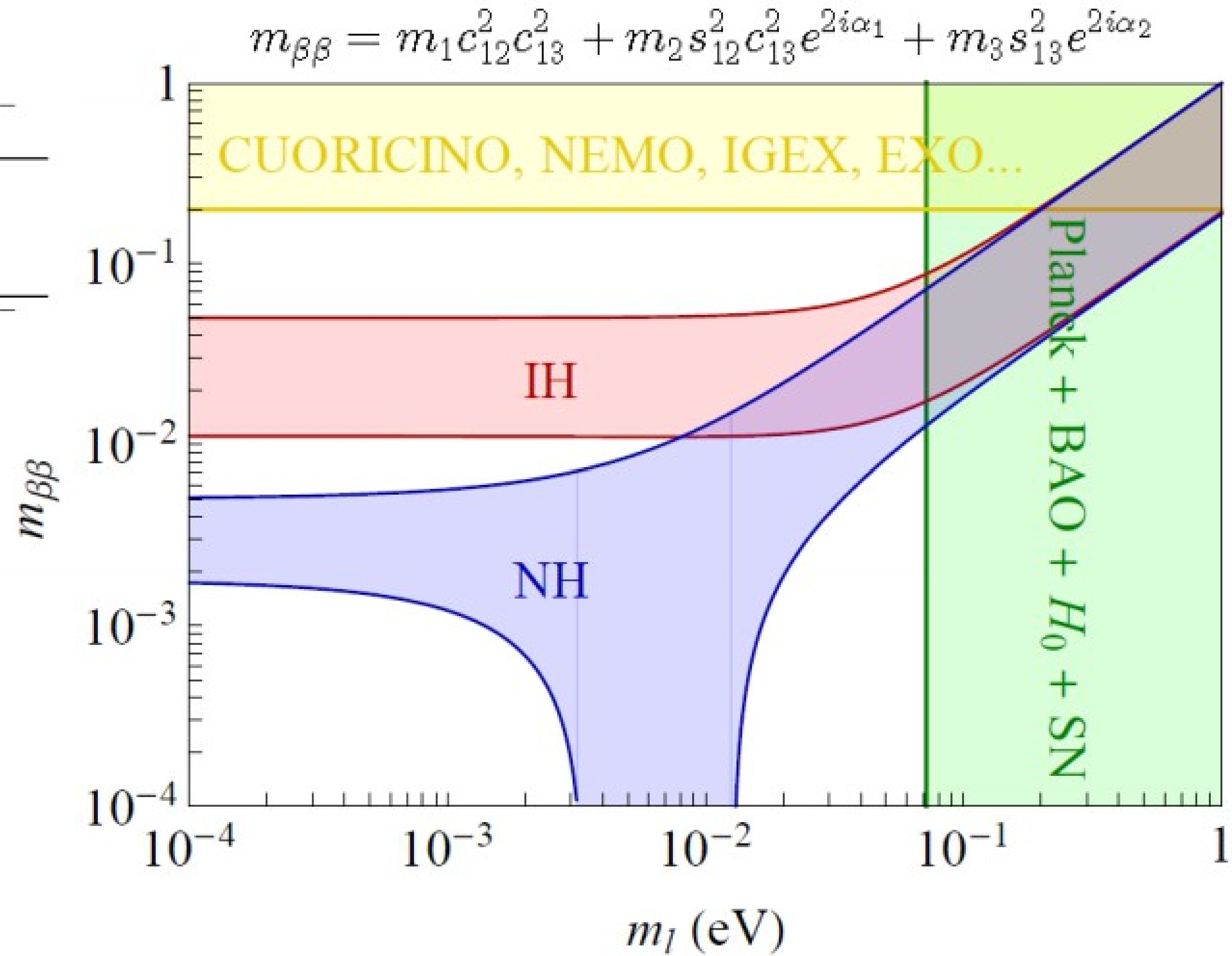
- There is a direct link between lepton number and lepton flavor violation in this model



Observables at low energies







Plot updated from Blennow et al, 1005.3240

$W_L - W_R$ mixing

$$W^{\pm}_{\mu} = W^{\pm}_{L,\mu} \cos\theta_+ + W^{\pm}_{R,\mu} \sin\theta_+$$

$$W'^{\pm}_{\mu} = -W^{\pm}_{L,\mu} \sin\theta_+ + W^{\pm}_{R,\mu} \cos\theta_+$$

$$\sin\theta_+ = \frac{g_R}{g_L}\left(\frac{M_W}{M_{W'}}\right)^2 \sin 2\beta$$

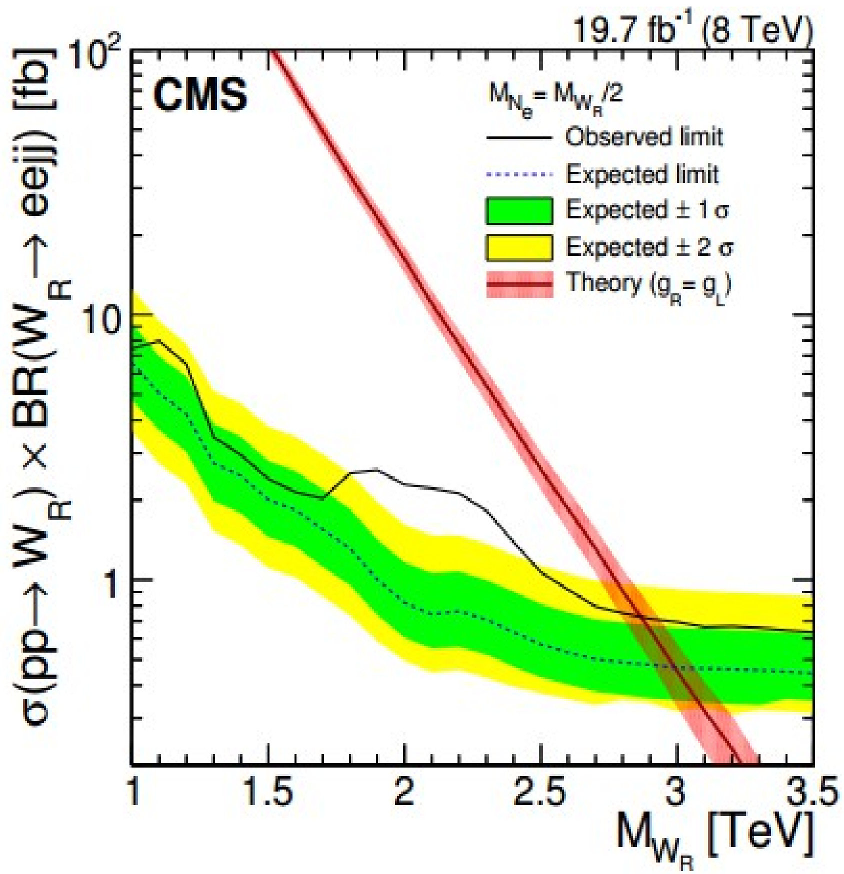
$$\langle\Sigma\rangle = v_H \begin{pmatrix} \cos\beta & 0 \\ 0 & e^{i\alpha_\Sigma}\sin\beta \end{pmatrix}$$

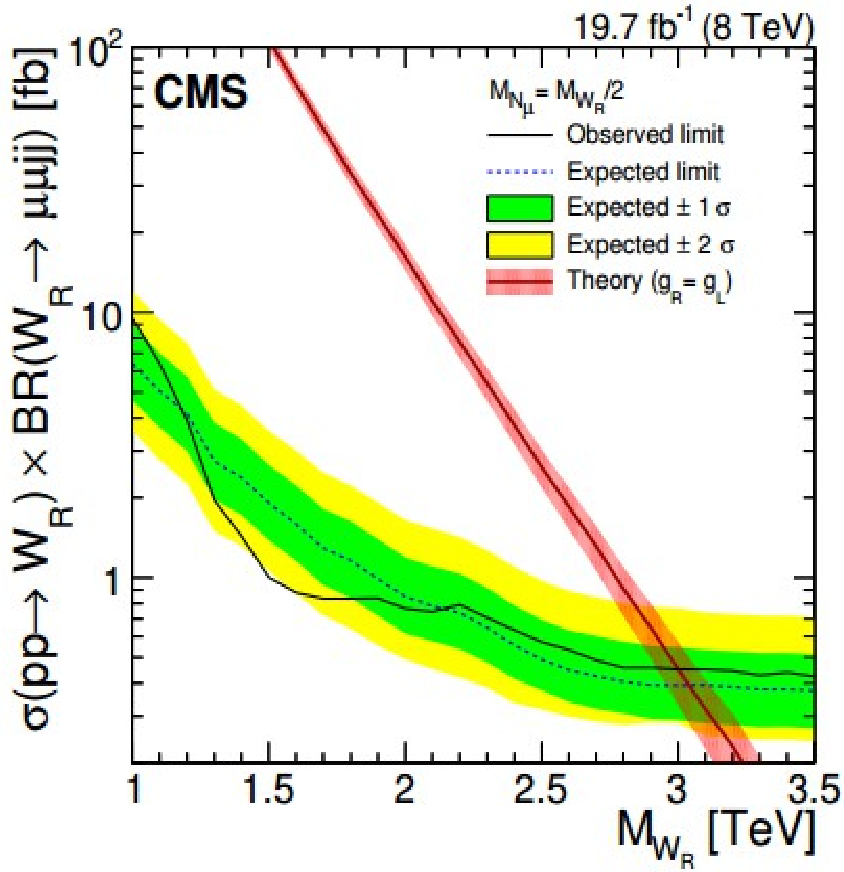
$g \simeq 0.65$

$g_R \sim 0.45 - 0.6$

Neutrino signals at colliders

In 2014, CMS reported a small excess in eejj events which could be associated to W' decaying via a right handed neutrino





CMS collaboration, 1407.3683